Intergrid: A Future Electronic Energy Network?

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***Abstract*—Anticipated widespread usage of new power electronics technologies in electrical energy generation and consumption is expected to provide major efficiency improvements, while the deployment of smart grid technologies should improve the utilization and availability of electricity. This paper explores possible relationships between these two trends. Starting from an analysis of current and expected trends in the generation, transport, and consumption of electrical energy, this paper contemplates possible future ac and dc electronic power distribution system architectures, especially in the presence of renewable energy sources. The proposed nanogrid-microgrid–…–grid structure achieves hierarchical dynamic decoupling of generation, distribution, and consumption by using bidirectional electronic power converters as energy control centers. Several possible directions for modeling, analysis, and system-level design of such systems, including power flow control, protection, stability, and subsystem interactions, are briefly discussed.**

***Index Terms*—Electronic power converters, electric power distribution, intergrid, microgrid, nanogrid, power conversion systems, power converter modeling, system integration.**

I. Introduction

IN TODAY'S climate of enhanced apprehension about the clash between energy and environment, it is becoming conventional wisdom to expect that massively increased utilization of electricity in the energy production, transport, and consumption will provide the necessary means for a sustainable future. Major energy savings and exciting improvements in quality of life will be enabled simultaneously by new electronic energy conversion systems in all energy consuming devices, from pacemakers and home appliances to electric vehicles and industrial waste processing plants. All alternative, sustainable, and distributed energy sources, as well as energy storage systems, will be connected to the electric grid through agile and efficient power electronics converters. The current electric grid will be hugely expanded and made much smarter by equipping it with advanced information collecting infrastructure. This emerging electricity network, where practically all loads and sources are electronic power converters, will require new concepts for electronic control of all energy flows in order to improve system stability and availability, while greatly increasing power density and energy efficiency. The approach could be analogous to the emerging power management technologies in autonomous power systems, from portable devices and datacom equipment to cars, airplanes, ships, and trains [1], [2].

However, extrapolating the experience from 0.1–1000 kW applications to grid applications is wrought with uncertainty. As the latest resurgence of developments in high-voltage dc (HVDC) transmission illustrates [3]–[7], the performance, reliability, and affordability of electronic power converters at 10–1000 MW power levels still need significant further improvements, and the fundamental concepts of energy flow and protection in electric power systems will need serious rethinking.

Assuming that these developments could happen in the near future, the main goal of this paper is then to contemplate on how power electronics may change the way electric energy is produced, transported, and used, and hence enable a sustainable future society. The discussion is organized around the following major questions:

1) Will electrical energy play a major role in solving the energy challenges of society?
2) Can today's electric grid technologies provide adequate solutions?
3) How power electronics could enable new electrical systems for sustainable energy society?

This paper is based on the reasoning presented in several previous papers [1], [8], [9], and follows the ideas from the plenary presentations at IEEE APEC 2011 [10], IEEE PEDSTC 2012 [11], and IEEE ECCE Asia 2013 [12]. The first version of this paper appeared in [13].

II. Predominance of Electric Energy

Consider today's total energy flow in the U.S. shown in Fig. 1(a) as an example of total energy production and consumption in developed societies. The primary energy sources are: petroleum, natural gas, coal, nuclear, and renewables (including large hydro-power generation). The residential and commercial consumption (buildings and public spaces) is around 40%, while the remainder is equally split between industrial and transportation usage. A remarkable change that has happened in the late industrial societies of the 20th century is the continuous increase in the share of electricity in the energy transfer and final consumption, from practically zero to over 40%. So, an interesting question is whether similar trends will continue and why.

A hypothetical energy flow that could exist in the developed world within 10–30 years is illustrated in Fig. 1(b). It is based on three major assumptions. First, it seems plausible to assume that the quality of living will continue to rise while the

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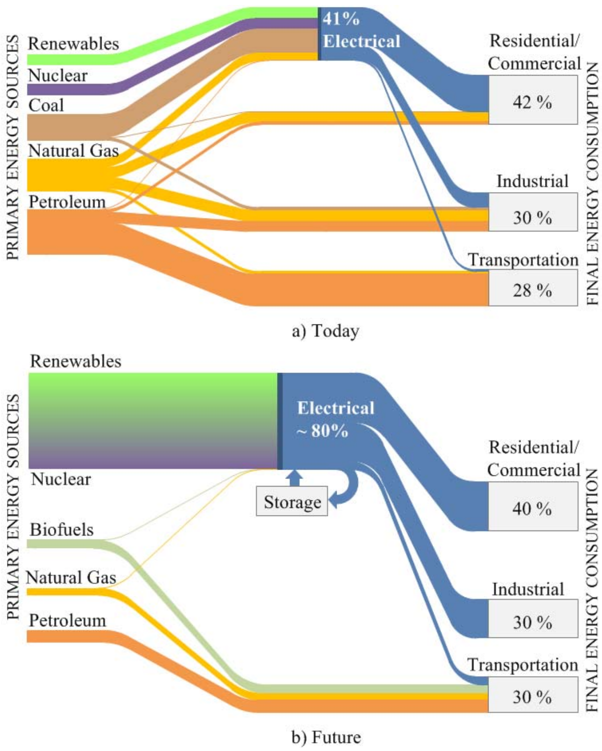

Fig. 1. Total energy production and consumption in developed societies. (a) U.S. energy flow [14]. (b) Possible energy flow in sustainable future.

total energy consumption and the types of usage will remain roughly unchanged. This increased energy efficiency would be possible due to the technological and behavioral advances that will enable higher quantity and quality of goods and services to be produced with less energy.

The second assumption is that if the human society chooses not to pollute itself out of existence, it will find ways to significantly reduce the use of hydrocarbons as the primary energy source. However, due to their unsurpassable energy density, petroleum, natural gas, and biofuels will probably remain dominant in transportation, especially in air and on water. Since a large part of the land transport could also be powered by electricity (rail, electric, and plug-in hybrid electric vehicles), it may be possible that only 20% of the total energy usage will come from hydrocarbons. Based on today's knowledge, it means that the 80% of sustainable energy might come from some mix of nuclear and renewable sources.

Last, it seems safe to assume that most of the energy coming from the sustainable sources will be converted to electricity before it is used anywhere else. Obviously, due to the large variability of renewable sources, their large penetration cannot happen without significant energy storage capacity and increased long-distance transmission capability.

As one can observe from Fig. 1(a), in developed societies already more than 40% of energy is consumed in the form of electricity. The two remaining major nonelectric uses of energy are heating and transportation; however, both could experience dramatic changes in the future. Although the efficiency of direct conversion of primary energy to heat can only be reduced by intermediate conversions to/from electrical energy, the efficacy of surrounding processes (e.g. simplified energy distribution, reduced heat loss, pollution remediation) and the ability for fast and precise control of the power, often favors electricity. Similarly in transportation, the advancement of hybrid-electric and electric vehicles, all electric ships, more-electric aircraft, in addition to the already widespread use of electrical traction in rail vehicles, will change the energy mix more toward electricity.

If the energy flow scenario from Fig. 1(b) could be expected in 10, 20, or 30 years, it would require electric energy infrastructure that is double of todays. Furthermore, the existing power system infrastructure is aging and inescapably facing not only an update but also more likely complete reconstruction in the future [15]–[17]. The statistics show an increase in grid outages and blackouts in the last 30 years [18], [19], and the grid infrastructure is a global concern, since the majority of installed transmission and distribution equipment has experienced service duty in excess of 30 years [20]. All of this implies that in the developed world, we could be facing the need to build a new electric power system with twice the size of the one we have today, within one generation. At the same time, the new electric power systems that will be built in the developing world will be several times as big. This opens enormous new challenges and opportunities.

III. Electric Power System Today

From its beginnings in the early 20th century, the structure and the organization of the power grid underwent a very slow evolution. The generation has always been centralized; the transmission features a mesh network structure, and the distribution organized as a radial network provides the electric energy at the lover voltage level to the end-consumers. This very well-known structure is shown in the simplified form in Fig. 2(a), illustrating the major components of the power system: production, transmission, distribution, and consumers, interconnected through the power lines and substations.

This conventional power system is intrinsically slow due to the fact that it is mechanically controlled, where due to the frequent action, electromechanical devices such as governors, switchgear, tap changers, and switched capacitors, tend to wear out very quickly compared to static electronic devices [21]. Future grid should be controlled electronically rather than mechanically [22], [23], and the stability of the power system could be improved by actively controlling active and reactive power flow. For instance, it has been anticipated that before year 2030, grid will be a fully automated power delivery network, featuring a two-way flow of electricity and information between the production, consumption, and all points in between [24]–[28] It takes time to reach these goals, and the future power grid will not emerge instantaneously, but will be a migration rather than a sudden transformation [29], [30]. This course has already started with the smart or responsive grid initiative [31]–[33] seen as the concept featuring enhanced sensing, actuation, control and operational benefits. To meet these goals, smart grid must, by default, feature dynamic pricing, real-time system operation data sharing, enhanced transmission and distribution automation and

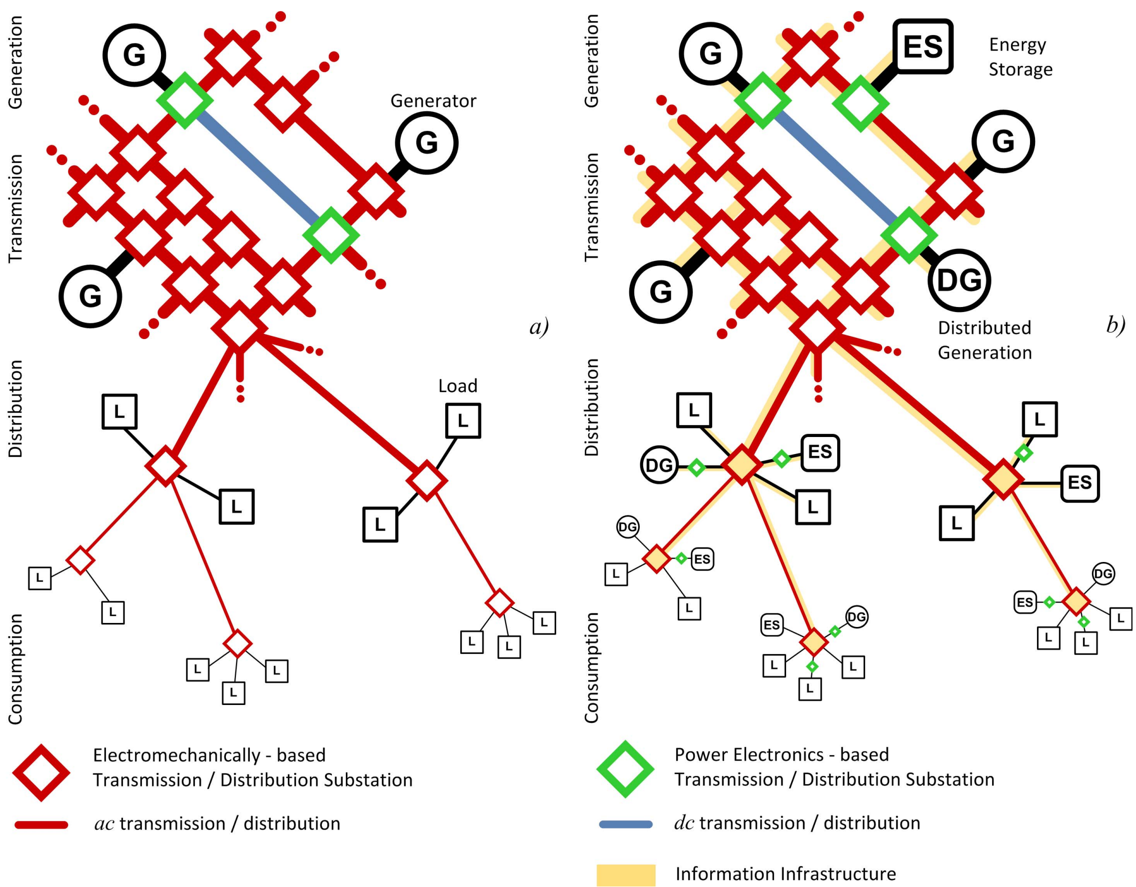

Fig. 2. Illustration of electric power system today. (a) Traditional 20th century grid. (b) Smart grid.

accurate exchange of data between the utility company and energy users that are effectively delivered to each one via an advanced metering infrastructure (AMI). The developments beyond today's concepts for smart grid will be determined in large by the current and expected penetration of power electronics into the all aspects of electric power generation, transmission, distribution, and consumption.

A. Power Electronics in Energy Consumption

Over the last 40 years, there has been an overwhelming trend to provide all electric energy to the final load equipment through fast and precise electronic power converters in order to improve load performance and energy efficiency [33]–[36]. None of the electronic devices that have pervaded our lives—from phones to the life-support equipment—can directly use the electricity from the ac mains; it must first be converted to dc of appropriate voltage by electronic power supplies. Most of the electric motors used in elevators, ventilation, pumping, heating, air-conditioning, refrigeration, food processing, fabric care, etc. are today being powered through electronic motor drives. With the already widespread use of electronic ballasts for fluorescent, HID, and LED lighting, and with the forthcoming elimination of incandescent lights, soon all electrical energy for lighting will also be processed electronically. Finally, with the traditional cooking equipment being replaced with microwaves and induction heating, over 80% of the total energy usage in newly equipped commercial and residential buildings will be processed through power electronics. Similar percentages of the total electric energy consumed in industry and transportation are already being processed by power electronics converters [37], [38].

These trends are fundamentally changing the nature of the loads on the electrical grid, from inductive and resistive to capacitive and nonlinear. As the power converters make the final load more robust to the variations in the grid, they also present a negative incremental resistance behavior to the grid. These constant power loads (CPL) react to a voltage sag with the increased current draw in order to prevent any disruptions to the load. Furthermore, the power converters can produce large amounts of high-frequency electromagnetic interference (EMI) unless attenuated by passive filters, which in turn add significant high-frequency dynamic behavior to the grid that never existed before.

B. Power Electronics in Distributed Generation

Although distributed generation (DG) was the rule rather than an exception in the early days of electric energy production [39], it has been almost completely replaced by the large-scale centralized generation in the second half of the 20th century. Recently, rapid commercialization of the renewable energy sources [37] has resulted in increased deployment of low, medium and high power DG sources as well as energy storage (ES) systems. Invariably, renewable DG and ES sources are interfaced to the grid with the assistance of power electronics converters. Fast, digitally controlled converters offer endless possibilities for the most optimal utilization of renewable resources. Moreover, power electronics-based DG can enhance power system controllability due to the fast dynamic response to the power system disturbances and deviations of the voltage and frequency.

Although future energy sources will unavoidably represent a mix of different technologies, wind generation is most likely to remain the dominant segment of the renewable industry [40]–[42]. The most common, doubly-fed induction generator (DFIG) wind turbines [43], [44], require power converters rated at about 30% of the nominal power. However, with the recent fault-ride-through requirements [45], DFIG would need power converters rated at 100% of the nominal power, which could create a shift toward the full-power converter wind turbine systems, which also provide significant flexibility and performance improvements.

While increasing power availability, distributed generation may have negative impact on protection coordination, voltage regulation and voltage flicker that can be caused by the intermittent behavior of the renewable sources, especially wind turbine systems [46]. Also, the conventional voltage regulation is commonly based on radial power flow so distributed generation can lead to both, overvoltage and undervoltage conditions [47], [48], and by introducing inversion in the power flow that is not common for the radial networks, distributed generation can affect the stability by directly influencing hierarchical protection scheme and relay coordination [49]. Power converters for renewable resources, and in general, all distributed generation, work as current sources [50], and every grid-connected inverter forms a dynamic system with the grid, so unintentional dynamic interactions may occur at the interconnection point, causing instability [51], oscillations [52] or harmonic distortions [53].

C. Power Electronics in Power Transmission

A network able to handle intermittent distributed renewable generation, and supply fast and widely variable electronic loads, could be implemented by utilizing power converters for fast control of the energy flows in a changed power system structure [33]–[35]. However, today's power grid employs power electronics only for the fast dynamic control at transmission level [3], [4].

The high voltage direct current (HVDC) transmission has been developed and used for bulk power transmission over very long distances and to interconnect two ac systems with the different operating frequencies. Furthermore, it can significantly influence and improve the transient stability of the power system. There are two major types of HVDC systems: the older, thyristor-based line-commutated, current source HVDC is usually used with the overhead lines, and the newer, IGBT-based force-commutated, voltage source converter (VSC) HVDC is often employed for cable and multiterminal transmission. The line-commutated HVDC is used for long-distance very high power transmission, up to 6.5 GW through the lines with up to ±800 kV [7] whereas the VSC HVDC systems have been used for transmission up to 1.2 GW with the ±320 kV cables and could be suitable even for some distribution-level applications, e.g. through underwater or underground cables.

Similarly to the HVDC technology, flexible ac transmission systems (FACTS) have been offering new solutions and opportunities for controlling power and improving the transmission capacity utilization [21]. In the form of the thyristor-based static VAr compensators (SVC) and VSC-based static synchronous compensators (STATCOM) and universal power flow controllers (UPFC), FACTS devices are opening numerous possibilities in controlling the power and improving the performance and reliability [55] of the centralized bulk power transmission systems.

Line-commutated HVDC has large reactive power consumption and cannot operate in weak systems. VSC based HVDC can dynamically reverse the direction of the power flow very fast and has the ability to supply reactive power to the grid independently of its active power transmission, thus providing a major capability for the grid stability improvement [5], [6]. Furthermore, the recent resurgence of the modular multicell converter concepts [96]–[98] opens new possibilities for the massive use of lower cost power conversion technologies in the high-power medium and high-voltage applications. This is expected to enable wider usage of full-power electronics conversion in the distribution as well as transmission networks, e.g. for remote oil and gas platforms, and large off-shore wind farms.

D. Smart Grid

In the attempt to accommodate the fast changing nature of the end-user loads and embrace the distributed renewable sources, the smart grid concept has been developed [54]. It is illustrated in Fig. 2(b) with the addition of distributed generation (DG), energy storage (ES), and an information infrastructure that goes beyond the traditional system control and data acquisition and energy management systems (SCADA/EMS). It is expected that this new infrastructure will enable the grid to predict and respond fast to changing power demands and abrupt source rescheduling and faults, with clear goals to increase productivity and efficiency [56]. Empowering consumers and enabling energy trade market where end-users can decide to use energy when affordable and save it when it is not, is another idea behind the smart grid concept.

Due to the fact that power-flow control still remains electromechanical, the described architecture does not yet completely resolve the coupled dynamics problem of the distributed generation and consumption. The concepts that imagine millions of individual sources and loads being controlled by the utility operator are unrealistic, while local interactions of these sources and loads will become intractable, especially whenever the local (neighborhood) generation is providing a significant amount of the local consumption. It seems that in future power systems with sizeable dispersed generation, the distribution systems cannot serve only for the load and source agglomeration, but must be hierarchically delegated a substan-

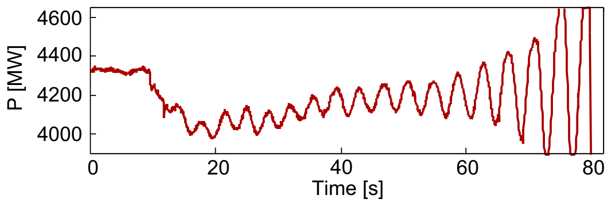

Fig. 3. Recorded system dynamics of a real power flow during the August 10th, 1996 event - (California and Oregon Intertie) [19].

tial authority over local voltage and frequency regulation in addition to the energy management.

E. Limitations of the Electric Grid Today

Despite highly increased data collection through the information infrastructure, the proposed smart grid concepts still lack a vision for automatic power flow control at all levels, from generation to transmission, distribution, and consumption. Power system control centers would still be dominantly relying on operators' responses and actions, which vastly increases decision time constants, and can lead to massive power system blackouts as seen numerous times in the history of electric grid [57]. Fig. 3 shows a recorded system dynamics of a real power flow on one of the transmission lines during a blackout [19]. As seen on this figure, there was a period of about one minute from the moment when the first transmission line tripped, to the moment when low-frequency system oscillations became severe. Obviously, that one minute was not enough for human operators to reconfigure the grid and prevent the cascaded event to happen.

The massive use of power electronics for the fast control at the loads and sources described in the previous sections opens new opportunities for automated power flow control, but at the same time will generate many new problems if the grid structure remains unchanged. This is illustrated by simulation of the two contrasted distribution systems shown in Fig. 4. The first system [Fig. 4(a)] depicts a 750-kVA distribution transformer providing the power through overhead lines to a constant power load (CPL)—here shown as a regulated motor drive with three-phase PWM front-end rectifier. The second system [Fig. 4(b)] feeds the same load through the voltage source converter (VSC) and an underground cable. Both systems were modeled with average models, and the simulation results for both three-phase currents and voltages at the CPL terminals are shown in Fig. 4(c) for the load step from 10% to 50% of the rated power at 10 ms. In the first system, currents and voltages started to oscillate after the load step was applied because the incremental negative resistance seen at the input of the CPL became smaller than the inductive output impedance of the overhead lines and the distribution transformer. This is avoided in the second system by designing the VSC to have very low output impedance and using the cable (dominantly capacitive) so that the output impedance of the source system (VSC with a cable) drops with the frequency and stays smaller than the incremental negative resistance of the CPL even at full load.

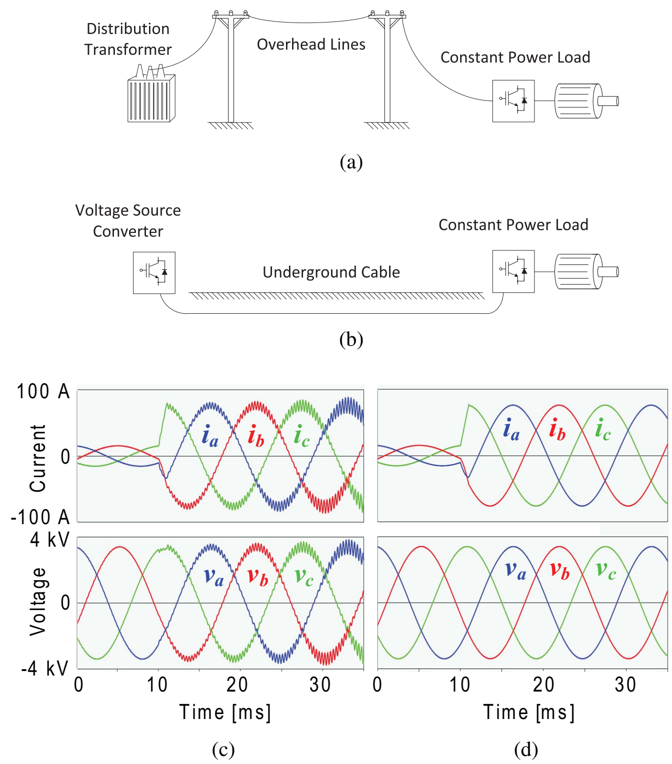

Fig. 4. Distribution system stability example. (a) Traditional power distribution to an electronic load. (b) Distribution with power electronics and underground cables. (c) Transients in (a). (d) Transients in (b).

IV. Future Electric Power Systems

The architecture of an electric power system, including subsystem voltage and current ratings, is a major determinant for the system structural and thermal feasibility, safety, availability, size, weight, power and energy efficiency, reliability, and ultimately for the cost of energy utilization. Although most of these are quantifiable physical variables, the sheer size of the design space in most applications, coupled with the uncertainty in the objective function, allows for numerous equally optimum system architecture solutions.

As shown in the previous example, power converters can enable the simplification of the design problem by separating a complex system into a large number of smaller, well-defined, and easily optimized subsystems. The utilization of the energy sources and the power delivery to loads can then be optimized independently of the power distribution architecture, which is primarily determined by the type of application and the power level. In such electronic power distribution systems (EPDS), the dynamics of electric energy generation, distribution, and delivery could be fully dynamically decoupled by using separate source converters, load converters, and power distribution converters, as is already a common practice in smaller autonomous power management systems [9].

Contemporary trends, concerns about sustainability, and higher availability of smaller generating systems (i.e., solar cells, wind turbines) have opened new opportunities for electricity users to generate power on-site. The presence of distributed generation with associated electronic power converters, which are not controlled by the electric power utility operator

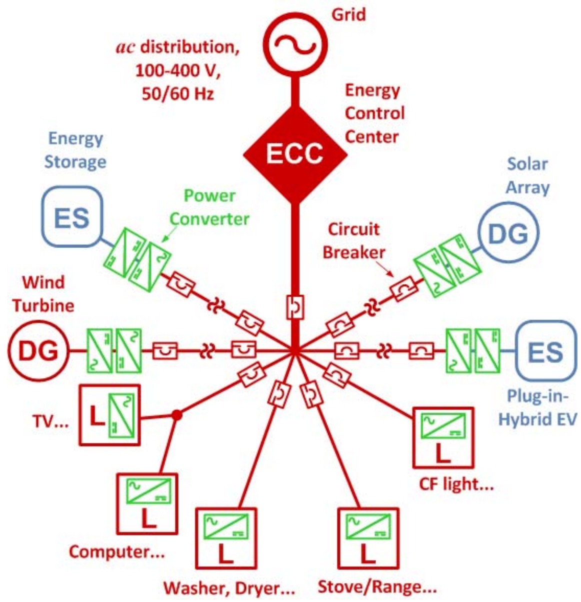

Fig. 5. Contemporary vision of smart nanogrid in residential home.

has required fresh thinking about how the electric grid is built and operated, at least at the distribution level. The so-called microgrid is widely known and accepted concept that comprises energy storage and a larger number of generating units in order to get the most from the naturally available renewable energy sources while minimizing architectural changes and operational disruptions of the existing power grid [58]. Based on these considerations, several candidates for EPDS architectures are illustrated below. The discussion is organized around the application in future sustainable residential buildings, but many ideas come from and could be applied in the other EPDS applications mentioned above.

A. AC Nanogrid

At extreme, the microgrid concept can be applied to residential electrical system at the low power level (10–100 kW) as shown in Fig. 5, when it may be termed as a nanogrid [59]–[62]. Combined with net-metering, communications, and remote control, such nanogrids could become building blocks of the future smart grid. Contemporary homes are envisioned to be energy sustainable and powered by a mix of renewable energy sources, together with utility grid. The sources would mainly include photovoltaic solar cells (PV), wind generators, micro-turbines, fuel cells, and local energy storage. Plug-in hybrid electric vehicles (PHEV) are also expected to become an inherent part of the future home [63].

In the contemporary homes like the one shown in Fig. 5, the majority of the electrical household functions depend on the power electronics to convert electrical power into the form and amplitude required by the sources or loads. Through appropriate design of these devices and by operating them in a coordinated fashion, net residential fuel-based energy use can be reduced dramatically, while simultaneously increasing the perceived comfort levels in terms of lighting, temperature, water, and air quality.

In the smart grid concept, the energy control center (ECC) in Fig. 5 consists of a smart power meter and remotely operated breaker panel. ECC is able to communicate with the electric power utility operator for the energy trading purposes, and also acts as the data acquisition unit collecting and recording the power flow data not only from/toward the grid, but also from all the converters and smart appliances in the home. The major features that distinguish architecture of the shown electrical system in comparison with today's conservative home include the ECC, renewable energy generation, PHEV and/or local battery storage, as well as the ability to program and communicate with most of the system components (distributed intelligence capability).

Power converter for the PV is most commonly unidirectional two-stage converter featuring the step-up (boost) dc–dc converter stage and a single- or three-phase voltage source inverter stage for adequate interface with the utility grid [64]. New converters for small wind turbines are also two-stage power converters, comprising the three-phase PWM rectifier and a voltage source inverter. Energy storage and PHEV typically require bidirectional dc–ac converters for the optimal battery utilization on one side, and ac-line interface at the other.

Household loads more and more contain power electronics converters that optimize their operation and boost up the efficiency, as illustrated in Fig. 5. A modern washer, for example, features the variable speed drive that provides a maximal torque per current to the brushless motor, and thus more efficiently utilizes the energy compared with the conventional pole-changing induction motor often found in the older type of washers. Even once the biggest resistive load in a home, a stove, is being replaced with the one featuring induction heating and now becomes an electronic load to the system. Lower power consumer electronics devices, such as TV, computer, audio, and other portable ones, inherently comprise the power electronics circuits for operation, and boast with the power aware function enabled by it [65]. It is interesting to note that practically all electronic loads have two-stage power conversion, where the front-end converter consists of a rectifier, electromagnetic interference (EMI) filter, and often a power factor correction (PFC) circuit.

Described system can work in two major modes of operation, grid connected, and stand-alone mode, and perform two major transitions, islanding, and synchronization. Together with the ECC, the bidirectional power converters from the PHEV and/or energy storage are responsible to isolate the home from the utility grid in the case of a fault or other abnormal grid conditions, perform the frequency and voltage regulation of the home ac-line in the stand-alone mode, and synchronize and reconnect the home to the utility grid without load power interruptions [66], [67]. This also presents the opportunity for demand-response operation while in the grid-connected mode [63].

In order to dynamically decouple the nanogrid from the rest of the power system, a full-power bidirectional converter could be used instead of the smart power meter in the ECC in Fig. 5. In that case, the whole nanogrid of the building is seen by the utility grid as a single electronic load/source, dynamically independent of the grid but dispatchable by the

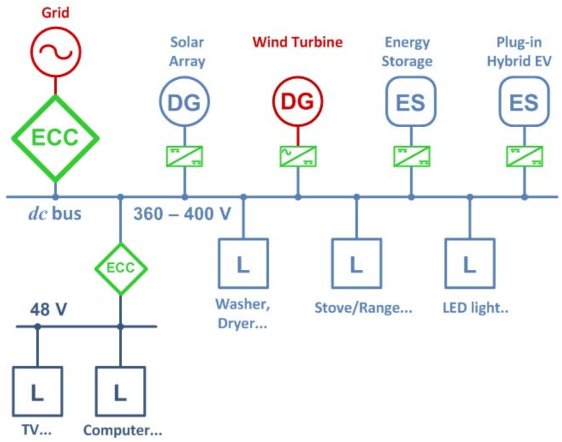

Fig. 6. DC-based nanogrid in a future home.

utility operator. The ECC is entrusted with the operation of the local renewable generation, load shedding, utilization of the static or mobile battery (PHEV) energy, and other power management functions, as well as nanogrid stabilization and advanced, active islanding in the event of outages or other low frequency disturbances on the utility side. In such hierarchical grid architecture, the nanogrids are fully dynamically decoupled from grid through ECC, so that their internal architecture is completely independent and can have different voltage, phase, and even frequency, from dc to kilohertz.

B. DC Nanogrid

Once the nanogrid is dynamically separated from the rest of the grid, it is easy to envision that the future building electric systems could be based on a dc nanogrid, as shown in Fig. 6. Compared to the ac nanogrid architecture in Fig. 5, dc nanogrid brings many advantages, starting with fewer power converters, higher overall system efficiency, and easier interface of renewable energy sources to a dc system [68]–[70]. There are no frequency stability and reactive power issues, and no skin effect and ac losses. What is more, the power electronics converters within consumer electronics, electronic ballasts, LED lighting, and variable speed motor drives can be more conveniently powered by dc.

DC nanogrid in future buildings is envisioned to have two dc voltage levels: a high-voltage (380 V) dc bus powering heating, ventilation, and air-conditioning (HVAC), kitchen loads, and other major home appliances, and a multitude of low-voltage (24 or 48 V) dc buses powering small tabletop appliances, computer and entertainment systems, and LED lighting. The 380 V dc level is chosen to match the industry-standard intermediate dc voltage in consumer electronics with the PFC circuit at the input, so that conversion from ac to dc would involve only bypassing (or eliminating) the front-end rectifier and PFC in most contemporary appliances. The 48 V dc level coincides with the standard telecom voltage to facilitate adoption, increase efficiency, and provide enhanced safety when handling small appliances, while enabling aesthetically attractive designs with exposed electrical-structural elements. Beside the dc distribution systems already proposed for commercial and residential applications [71]–[75], similar dc power distribution systems are currently being considered for datacom centers in Japan and Europe [76]–[81], and are also being contemplated for PHEVs, ship, and aircraft power systems [82]–[84]. Several manufacturers already have on the market high power-density bus control modules that supply 48 from 380 V and are intended for these applications.

In higher voltage dc systems, fault current interruption is of particular concern. However, in the proposed nanogrid architecture, all power is fed from electronic power converters that are controllable and can provide active current limiting, thus reducing the need for electromechanical protection devices. The system could be even completely breakerless if all the source converter topologies comprise serial semiconductor switches which fail open in the case of catastrophic failures. This would also eliminate the need for significant over-sizing of the wiring and upstream converters that is traditionally used to ensure safe clearing of the electromechanical breakers in the case of faults. Therefore, such nanogrids may be able to provide increased energy efficiency, power density, and reliability, at possibly lower installation and operation costs. However, further research is needed on the development of physics-based models that quantitatively relate these variables while accurately describing system dynamical behavior, before new nanogrid architectures could be truly optimized and the described tradeoffs justified.

C. Intergrid

The proposed ac and dc architectures have several main distinguishing features:

1) at least a minimal level of local energy generation and/or storage;
2) interface(s) to the higher level system through bidirectional electronic power converter(s);
3) ability to operate in islanded mode, at least during transients;
4) all energy sources and storage connected through electronic power converters;
5) most loads connected through electronic power converters;
6) extensive communication and control capabilities, both internally and externally;
7) most (possibly all) protection and reconfiguration functions provided by the electronic power converters, without the use of thermo-mechanical switchgear;
8) step-up/down and isolation functions provided by the electronic power converters without the use of low-frequency transformers.

Although all of these features could be achieved either with ac or dc, the presence of the last two characteristics eliminates any natural advantage of the low-frequency ac systems, while all the features could be achieved more efficiently in a dc system. There is also a preference for linear bus structures instead of radial ones in order to naturally accommodate dispersed mixing of generation and consumption with bidirectional energy flows, reduce wiring, and simplify system construction and maintenance [85]–[89].

Similar architectures, for example, have been proposed for the dc-zonal power distribution system for future ships, [90], [91], where generation and propulsion are decoupled so that energy sources can be distributed as required by other considerations. The system flexibility and reconfiguration capacity are maximized by using a dual dc-bus feeder structure, and by sectionalizing loads into groups (zones) distributed along the ship, which are fed from redundant zone distribution converters.

The PHEV electrical system with its bidirectional charger/discharger, on-board batteries, and the generator powered by the internal combustion engine, as well as numerous on-board electronic loads, has all eight features listed above, and hence could be considered as a miniature picogrid.

At the highest power end, the existing congestions in the transmission system and the rising concerns for the grid stability with the increased penetration of renewable generation are increasingly being alleviated by the construction of new HVDC transmission lines to improve the power flow management at the utility level [92]–[95]. This will enable decoupling of the existing megagrid into many smaller and better controllable asynchronous sub-grids.

It is then possible to contemplate that the proposed architectural concept of the nanogrid could be extended hierarchically, so that a number of such semi-autonomous nanogrids with nECCs are combined to form a bigger microgrid system, which in-turn is interfaced to a higher level distribution through a substation μECC, and so on, as shown in Fig. 7. The resulting system is a hybrid mix of ac and dc architectures comprising …, pico-, nano-, micro-, …, mega- grids that are dynamically decoupled and hierarchically *inter*connected to form a novel electric power grid structure: the intergrid.

AC and dc nanogrids in Fig. 7 correspond to the systems shown in Figs. 5 and 6. Numerous nanogrids can be connected to a distribution network, but they are considered to comprise a microgrid only if the network is connected to the next upstream level through one or more bidirectional μECCs. The ECCs that interconnect various subgrids are not only bidirectional power converters, but also actually energy routers that provide load and source aggregation, data acquisition and agglomeration, command communication and distribution, and have sufficient authority to enable hierarchical distributed control of the whole grid. Every ECC is capable to communicate with all of the downstream components in the subgrid as well as with the next level upstream ECC, in order to fully utilize and optimize operation of the particular subsystem, and consequently influence the overall operation of the intergrid.

Containing a bidirectional converter, an ECC can control the continuous energy flow into and out of the subgrid, and can perform intentional or unintentional islanding of the subgrid depending of the fault nature in the upstream system. By utilizing power electronics converters for all distributed generation—including numerous renewable sources and storage facilities—it is possible to continue operating the subgrid during brief and long upstream power interruptions, thus enabling unprecedented security and resiliency of the electricity supply in the presence of natural and malevolent traumas. With emerging advanced control algorithms, the PV,

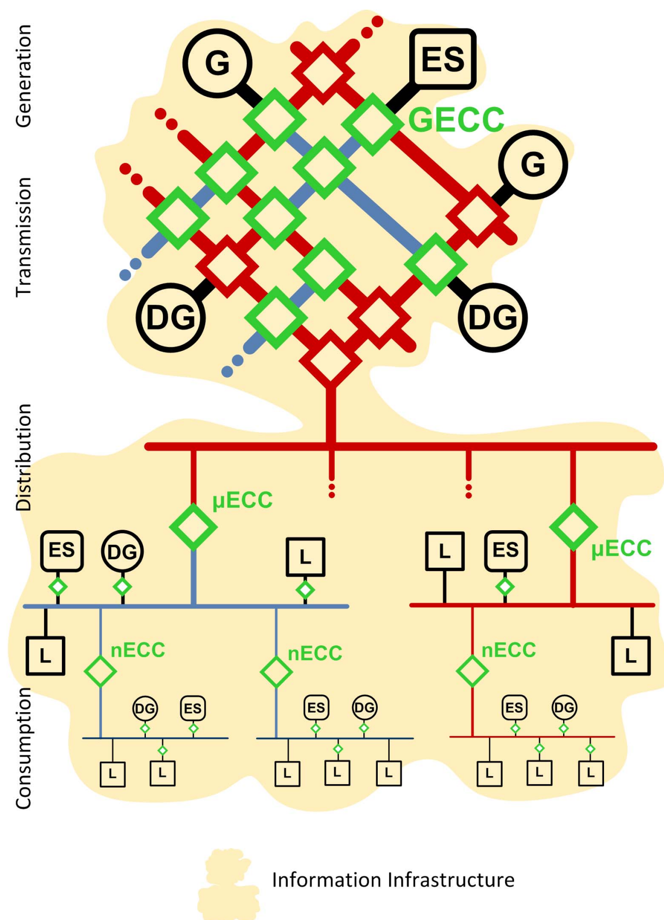

Fig. 7. Conceptual intergrid system structured as a hierarchical network of dynamically decoupled electronically interconnected sub-networks.

wind-turbine, and other source converters can regulate the bus voltage (and frequency for ac systems) and share the load current even in the weak-grid and stand-alone modes of operation, instead of only operating in the maximum-power-point tracking mode [99]. Obviously, this requires local demand-side management in order to balance the generation and consumption in the islanded subgrid, which is enabled by the presence of remotely controllable and fast point-of-load electronic power converters. Although most of the issues are very similar to the ones existing in the power grid today, they are much less complex and could easily be automated when dealing with tens of sources and hundreds of loads at every hierarchical level, instead of dealing simultaneously with thousands of sources and millions of loads at the whole grid level.

Furthermore, the contemplated intergrid concept is compatible with the existing grid and could be introduced gradually. New sustainable buildings, datacom centers, commercial and industrial areas, renewable and distributed generation facilities, small- and large-scale energy storage installations, as well as new power distribution in highly populated and congested areas (with no new available right-of-way) could all be economically implemented as ac or dc nanogrids and microgrids. These subgrids become dispatchable generation and load resources that can respond very fast to the commands from the power system operator and thus can participate in grid stabilization, voltage and frequency control, real-time pricing, and become an inherent part of the everyday grid operation. By utilizing the fast dynamic response of electronic power converters at each terminal of the VSC HVDC transmission lines, the energy could be easily rerouted between different subgrids, which can significantly reduce the need for the spinning reserve and facilitate the use of peaking power plants to compensate for the fluctuations in renewable energy generation.

Although the use of dc architectures facilitates and simplifies the dynamic decoupling of the interconnected subgrids, and more importantly improves the overall energy efficiency of the system, the disadvantage can be expensive infrastructure and protection components, as well as the fact that large-scale dc system implementation is not mature enough and still requires intensive research before standards can be developed and industry acceptance achieved.

V. Conclusion

Advancements in integration of power electronics components and converters are now enabling major improvements in the performance, power density, reliability, energy efficiency, and cost effectiveness of electrical power systems. These improvements are already evident in the low power systems within portable and stationary equipment and are increasingly affecting new designs for autonomous power systems in vehicles, airplanes, ships, advanced buildings, and for the renewable energy generation. This paper explored the possibility of extrapolating these trends to electrical energy supply to the whole society. Based on the presented assumptions and analysis, the following main conclusions could be made about electrification in the next 20–50 years.

1) Electricity will continue to be the most preferred medium for generating, transporting, and consuming the energy throughout the 21st century. Over three quarters of human total energy consumption will be provided by electricity. In order to satisfy these needs worldwide, electrical power systems will have to be built that are 3–5 times larger than the systems existing today.
2) Most of the electrical loads that were being installed today already process the electrical energy through electronic converters, and practically all of the electrical energy consumption will be via power electronics.
3) In almost all renewable energy generation and energy storage, the electrical energy must be processed through electronic power converters. It is also reasonable to assume that the path to the sustainable energy will lead through massively distributed generation and hence more than half of the future electrical energy will be supplied via power electronics.
4) The existing power grid, even when augmented with the pervasive information and communication technology, will not be able to reliably transport and distribute electrical energy in the presence of the future electronic loads and sources. One major problem is the slow response of the electromechanical actuators, controls, and protection devices relative to the fast electronic loads and distributed sources. The second major problem is the sheer complexity of the existing grid that is barely able to synchronize thousands of synchronous generators and will not be able to synchronize millions of independent electronic sources and loads.
5) The proposed approach for mitigating the complexity and the sluggishness of the existing electric grid is to implement the transmission and distribution substations as bidirectional electronic power converters, termed here as energy control centers (ECCs), which will separate the system into a hierarchical network of asynchronous ac or dc sub-grids. This intergrid architecture enables independent (islanded) operation of the sub-grids at all levels and very fast (sub-millisecond) continuous regulation of the power flow in all directions.
6) Besides supplying the energy router function for the energy management systems, the ECCs will provide voltage step-up/down using high-frequency transformers, current limiting, fault protection, and advanced metering infrastructure. By substituting the electromechanical switchgear and by limiting the fault currents to slightly higher than the nominal current values, the cost of the power system components outside ECCs could be significantly reduced.
7) Because the functions of current interruption, voltage step-up/down, and continuous power flow regulation will be implemented within ECCs operating at high-frequency ac, there will be no technical reason for the continued use of low-frequency ac in the power systems. Since dc–dc ECCs are inherently simpler (and lower cost), and since the dc conduction is naturally more efficient, the intergrid will increasingly move toward dc systems.
8) DC transmission and distribution is much more suited for the use of underground cables, which although more expensive than overhead lines can provide cost effective solutions due to the ability to use the existing "right-of-ways" along roads and highways, reduce environmental impact, and sustain less damage during extreme weather conditions. This could prove to be a key attractive feature of the intergrid in the densely populated developed world.
9) A major advantage of the intergrid is that it could be built bottom-up instead of the top-down approach that was used during electrification in the 20$^{\text{th}}$ century. This means that the distributed small-scale generation capacity and diverse local power distribution systems that are currently being deployed for rural electrification in the developing world will be effectively used as the building blocks of an emerging intergrid.
10) Technical obstacles to the intergrid implementation include the unavailability of high-power and high-voltage electronic power converters with acceptable cost, reliability, and lifetime. However, new technologies are developing fast and there is no physical reason to believe that the static power conversion will not out-

perform in all aspects the electromechanical conversion with moving components, as it always did in the past. Intergrid penetration will also strongly depend on the progress in our ability to model, understand, design, and dynamically control desired and undesired subsystem interactions in the new, electronic power distribution systems ranging from a few watts to the hundreds of gigawatts.

The implementation of the intergrid will drastically reduce security risks, increase resilience to natural disasters, enable transparent electrical energy markets, increase energy efficiency, and facilitate massive utilization of versatile sustainable energy sources, thus providing immeasurable boost to the economies and the quality of life. However, it will be hugely disruptive to the existing industry and infrastructure, probably on a scale that happened when the U.S. railway system was almost completely replaced by the Interstate Highway system in the second half of the 20th century.

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